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RESEARCH ARTICLE

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Abstract Individuals usually report for two objects of equal mass but different volume that the larger object feels lighter. This so-called size-weight illusion has been investigated for more than a century. The illusion is accompanied by increased forces, used to lift the larger object, resulting in a higher initial lifting speed and acceleration. The illusion holds when subjects know that the mass of the two objects is equal and it is likely that this also counts for the enlarged initial effort in lifting a larger box. Why should this happen? Under microgravity, subjects might be able to eliminate largely the weight-related component of the lifting force. Then, if persistent upward scaling of the weight-related force component had been the main cause of the elevated initial lifting force under normal gravity, this elevated force might disappear under microgravity. On the other hand, the elevated initial lifting effort in the large box would be preserved if it had been caused mainly by a persistent upward scaling of the force component, necessary to accelerate the object. To test whether the elevated initial lifting effort either persists or disappears under microgravity, a lifting experiment was carried out during brief periods of microgravity in parabolic flights. Subjects performed whole-body lifting movements with their feet strapped to the floor of the aircraft, using two 8-kg boxes of different volume. The subjects were aware of the equality of the box masses. The peak lifting forces declined almost instantaneously with approx. a factor 9 in the first lifting movements under microgravity compared with normal gravity, suggesting a rapid adaptation to the loss of weight. Though the overall speed of the lifting movement decreased under microgravity, the mean initial acceleration of the box over the first 200 ms of the lifting movement remained higher (P=0.030) in the large box (1.87±0.127 m/s^2) compared with the small box (1.47±0.122 m/s^2). Under normal gravity these accelerations were 3.30±0.159 m/s^2 and 2.67±0.159 m/s^2, respectively (P=0.008). A comparable trend was found in the initial lifting forces, being significant in the pooled gravity conditions (P=0.036) but not in separate tests on the normal gravity (P=0.109) and microgravity (P=0.169) condition. It is concluded that the elevated initial lifting effort with larger objects holds during short-term exposure to microgravity. This suggests that upward scaling of the force component, required to accelerate the larger box, is an important factor in the elevated initial lifting effort (and the associated size-weight illusion) under normal gravity.

Key words Lifting forces · Size-weight illusion · Microgravity · Human

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Introduction

When individuals pick up an object they perceive a certain heaviness of the object. The magnitude of this sensation is determined by object properties (e.g., mass, color, volume), environment properties (e.g., gravity), sense of effort (Burgess and Jones 1997), and subject characteristics (e.g., fatigue; Jones 1986). Although weight (object mass times gravity) may only be one of the factors that contribute to this sensation, it is often denoted as “weight perception” (e.g., Amazeen and Turvey 1996; Jones 1986). The origin of the perception of heaviness has been subject to debate for more than a century. In this debate the so-called size-weight illusion is frequently used as an experimental paradigm. The illusion, first described by Charpentier (1891), means that for two objects of equal mass but different volume subjects consistently report the larger object to feel lighter. The illusion does not seem to be dependent on one specific sensory source, since it occurs when skin pressure is blocked as well as when skin pressure is the only source of information (Jones 1986) and when vision is the only source of information (Ellis and Lederman 1993) as well as without vision (Gordon et al. 1991a). The nature of the size-weight illusion has been subject to research concentrating on the object properties that determine perceived heaviness (Amazeen and Turvey 1996; Cross and Rotkin 1975; Ross 1969; Stevens and Rubin 1970), on the dominant sensory system that contributes to perceived heaviness (Ellis and Lederman 1993; Masin and Crestoni 1988), or on the role of motor commands in the perception of heaviness (Davis and Roberts 1976; Ross and Gregory 1970).

In the initial phase of lifting an object, when the subject cannot yet respond to the actual object mass, increased lifting and grip forces (Gordon et al. 1991a, 1991b) and increased object accelerations (Davis and Roberts 1976; Gordon et al. 1991b) are found when objects of larger volume are lifted. In addition, increased anticipatory EMG levels are found (Davis and Bricket 1977). According to Davis and Bricket (1977), the initial forces are scaled to the perceived volume of an object. The (unexpected) larger acceleration due to the unconsciously enlarged lifting effort in the larger object could cause the sensation of reduced heaviness in comparison with the small object. Remarkably, the size-weight illusion does not disappear when subjects know that the mass of both objects is equal (Flournoy 1894). Following Davis and Bricket (1977), the elevated initial lifting force in the larger object also probably persists when subjects know that the objects have equal mass. Why should this happen? Through experiments under microgravity conditions, it has been shown that the weight as well as the inertial mass of an object influence the perceived heaviness (Ross and Reschke 1982). In comparison, in the programming of initial lifting forces, a persistent elevated initial lifting force in a larger object might be attributable to a persistent upward scaling of the force, necessary to overcome the weight of the object (i.e., to hold the object) or to a persisting upward scaling of the force, necessary to accelerate the object, or to both of them.

By definition, the force (f) that is used to lift an object under normal gravity constitutes a static component, required to overcome gravity: $m\times g=W$ (where m is mass, g is gravity, and W is weight) and a dynamic component: $m\times a$ (where a is acceleration):

$$f=m\times g+m\times a=W+m\times a \tag{1}$$

Under microgravity, g becomes negligible with consequent disappearance of the weight of the object. Possibly, subjects are able to adapt to the microgravity condition by largely eliminating the weight-related component of the lifting force. If this is true, the elevated initial acceleration of the large object relative to the initial acceleration of the small object would, firstly, disappear if exclusively the force, necessary to overcome the weight of the object, had been scaled upward under normal gravity and, secondly, remain unaffected by microgravity if exclusively the force, necessary to accelerate the object, had been scaled upward. Where upward scaling of the lifting force in the large object was related to some estimate of the object mass, Eq. 1 shows that both force components would be affected. Since the weight-related force component is usually the largest under normal gravity, an elimination of this component would result in, thirdly, a disappearance of the major part of the elevated initial object acceleration in the larger object. The effects, indicated by the three points above are further illustrated in an "idealized" numerical example in the appendix.

The current study was undertaken to find out whether the increased initial lifting effort in a larger box either persists or (almost) disappears under microgravity. To this aim, subjects lifted two boxes of different volume but equal mass during brief periods of exposure to microgravity in parabolic flights.

Materials and methods

Subjects

One female and three male subjects, 30–39 years old, participated in the study. None of the subjects had previously been exposed to parabolic flight conditions. All four subjects had passed a FAA class 2 flight physical examination and had received physiological training in a high-altitude chamber, prior to the experiment. All subjects had signed an informed consent and the experiment was approved by the Faculty's ethical committee.

Test protocol

Experiments were conducted on two flight days during the ESA parabolic flight campaign in December 1996 in the NASA KC 135 aircraft. During both flights, 30 parabolas were executed, each of them providing about 20 s of microgravity, preceded and followed by about 15 s of 1.8 g. Consecutive parabolas were separated by a steady-level flight lasting 2–5 min.

During both flight days, two subjects performed two series of seven whole-body lifting movements. In the two series of seven lifting movements, two different boxes of equal mass (8 kg) but different volume were used. Handles were attached to the left and right side of both boxes.

Subjects were strapped with their feet to the ground. During steady-level flight they sat on the ground. During the 1.8-g periods, each lay down on their back. As soon as microgravity started, they rose to erect posture, using a bar handle. After accommodating to erect posture for a few seconds, the subjects bent forward in a sagitally symmetrical way, flexing the knees as well as the trunk. Then the subjects grabbed both handles of the box and lifted the box to hip height (Fig. 1). After waiting a few seconds, they placed the box back on the ground and lay down on their back again, before the second 1.8-g period started. To prevent the subjects from being exposed to 1.8 g during the lifting movements, only one lifting movement was executed in each parabola. An assistant, sitting opposite to the subject, prevented floating of the box by holding it in place until just before the subject grabbed it and by grabbing it at the completion of the movement just after the subject released the box.

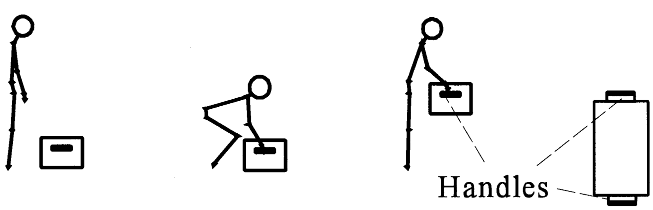

Fig. 1 Stick diagrams showing the whole-body lifting movement that was performed under microgravity and normal gravity. On the right side of the figure a top view of a box shows the location of the handles

To prevent the effect of a complete surprise in the first lifting movement, the subjects were aware of the fact that the mass of the boxes was equal and they were allowed to practice a few lifting movements with both boxes under normal gravity before the experiment started. The small box was 400×265×200 mm (width×depth×height) and the large box was 520×350×250 mm, so that the volume of the large box was 2.19 times that of the small box. The initial position of the center of mass of both boxes was 580 mm in front of the heels of the subject. Two subjects started with the seven lifting movements with the small box and two subjects started with the large box.

Control experiments (five lifting movements with each box) were conducted when the aircraft was on the ground, at the end of the first flight day. During the control experiments, the feet were strapped to the floor in the same fashion as during the parabolic flights.

Data collection

One SVHS video camera was rigidly mounted to the floor of the aircraft at a height of 0.95 m and a distance of 2.76 m from the sagittal plane of the subject and the mid-plane of the box on the right side. Two markers were placed on the box, three markers were placed on a reference frame, and two markers were placed on the right hand. Horizontal and vertical forces were measured by strain-gauge force transducers between both handles and the box. Force and video signals were synchronized using an electronic switch. The sample frequency was 50 Hz for the video camera and 200 Hz for the force signals.

Data processing

Marker coordinates were digitized, calculated relative to the reference frame, and filtered using a fourth-order Butterworth filter with zero phase lag at an effective cut-off frequency of 5 Hz. Before filtering, the standard deviation of the coordinates of nonmoving markers was 1 mm in horizontal as well as vertical direction, under microgravity as well as normal gravity. The two box markers were used to calculate the box center of mass at each instant of time. Numerical differentiation of the time histories of the box center of mass position with a Lanczos 5-point differentiation filter yielded the box speed. Subsequent differentiation of the box speed yielded the box acceleration. Force signals were summed over both box handles.

Statistical analysis

The instant of first visible upward box movement was determined with the aid of magnified trajectories of digitized hand and box marker coordinates. The initial lifting period, during which no effect of the subject's reaction to the actual box movement is expected in the measured mechanical parameters, was defined as the first 200 ms after lift-off. Mean values of the vertical box speed and acceleration and of the vertical force were calculated for this 200 ms. Using these values as dependent variables, an ANOVA was applied with gravity condition, box size, and subject as factors. Additionally, separate ANOVAs were applied to the trials of each gravity condition with box size and subject as factors. To check for learning effects in the microgravity condition, ANOVAs were repeated for this condition with the first compared with last three trials (within each box size) as an additional factor.

In addition, the peak box acceleration, the peak box velocity, and the peak box deceleration were calculated to obtain an impression of the effect of the subject's reaction to the (possible) increased initial box acceleration in the larger box. Again, ANOVAs were applied to the pooled as well as the separate gravity conditions.

Results

Effect of gravity and box size in the initial lifting period

The time series of the relevant signals for both boxes and gravity conditions were first averaged within subjects and then between subjects. In spite of the instructions to lift at a normal speed under microgravity condition, the averaged box speed and acceleration signals show that the lifting speed of the subjects was clearly lower under microgravity (Fig. 2). Consequently, a significant effect of gravity condition on the box vertical speed (0.28±0.014 m/s at microgravity, g_0, versus 0.40±0.016 m/s at normal gravity, g_1) and on the box vertical acceleration (1.67±0.092 m/s^2 at g_0 versus 2.99±0.106 m/s^2 at g_1) was found during the first 200 ms of the lifting movement (Table 1).

For the pooled g_0 and g_1 data at the first 200 ms of the lifting movement, the large box yielded a significant higher vertical acceleration (2.59±0.100 versus 2.1±0.098 m/s^2), speed (0.38±0.015 versus 0.30±0.015 m/s), and force (54.7±0.86 versus 52.2±0.83 N) compared with the small box (Table 1). Additionally, no significant interactions between gravity condition and box size were found, resulting in a preliminary indication that the effect of visual size on the initial lifting effort is preserved under microgravity.

Separate ANOVAs on the gravity conditions (Table 2) showed indeed significantly higher vertical accelerations for the large box compared with the small box under normal gravity (3.30±0.159 versus 2.67±0.159 m/s^2) as well as under microgravity conditions (1.87±0.127 versus 1.47±0.122 m/s^2). Likewise, a significant higher vertical box speed was found for the large box compared with the small box under normal gravity (0.44±0.025 versus 0.36±0.025 m/s) as well as under microgravity (0.33±0.018 versus 0.24±0.017 m/s). The averaged curves also showed a trend toward higher vertical forces in the large box compared with the small one under normal gravity as well as microgravity (Fig. 2), but this trend was not significant when gravity conditions were tested separately (Table 2).

Learning effects in the initial lifting period under microgravity

In order to find out whether learning took place in the sense that the initial lifting forces and box speed and acceleration either increased or decreased in time under microgravity, an additional ANOVA was performed where the first compared with last three trials of a box was added as a factor in the analysis. There were no effects of the first compared with last three trials on vertical box acceleration ($F_{1,32}$=1.9, P=0.179) or vertical box force ($F_{1,26}$=1.4, P=0.240) and a slight but not significant trend toward lower vertical box speed in the last three trials ($F_{1,32}$=3.5, P=0.070). This suggests that the lifting forces

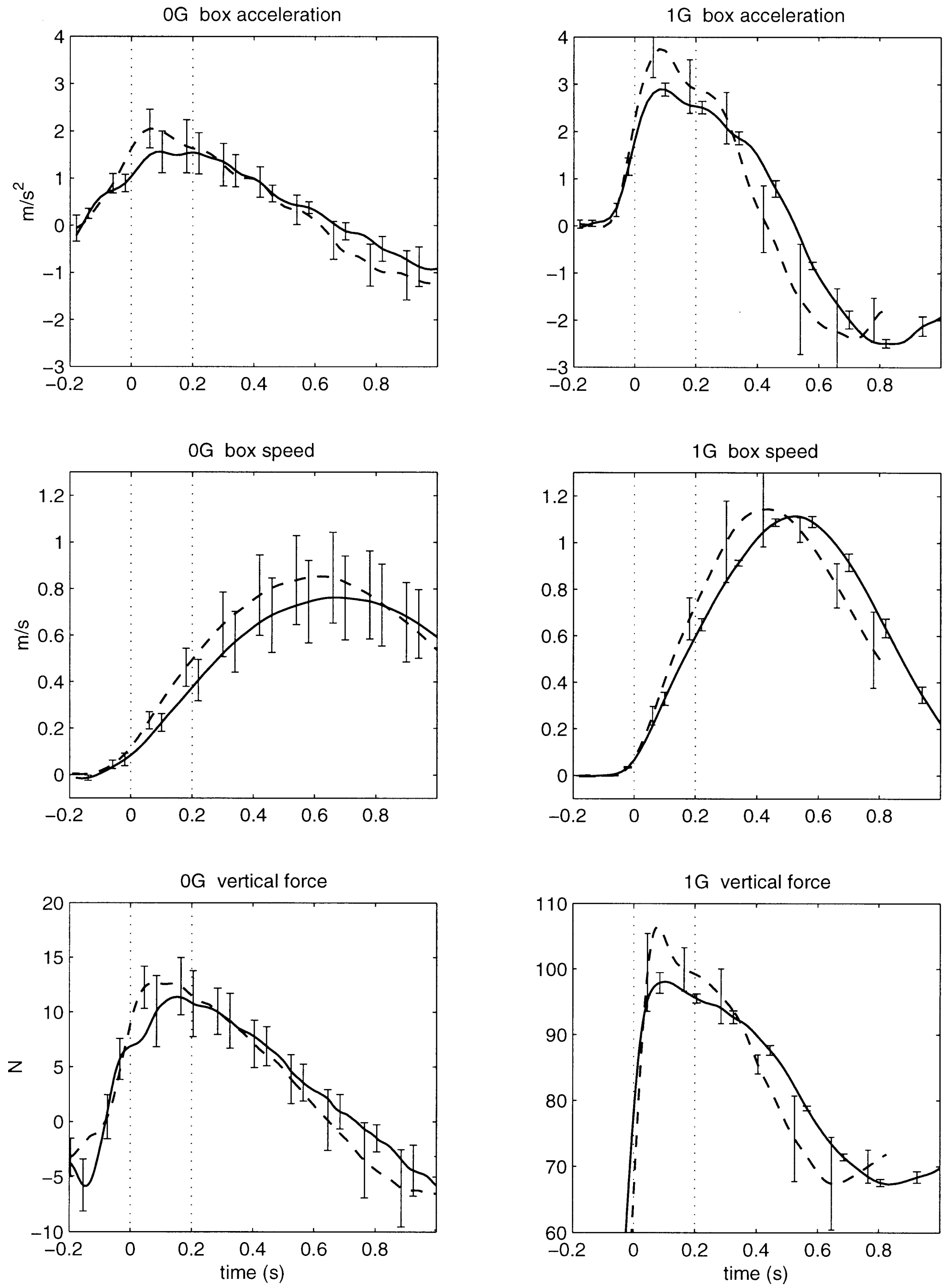

Fig. 2 Averaged curves of the vertical box acceleration (*top*), box speed (*middle*), and lifting force (*bottom*). *Solid lines* indicate the small box and *dashed lines* the large box. Curves were first averaged within and then between subjects. *Error bars* indicate the SE over subjects. *Vertical dashed lines* indicate the first 200 ms after the first visible upward box movement, which was the time period that was used for the statistical analysis of the initial lifting period. *Left*, microgravity, g_0; *right:* gravity, g_1

had been adapted to the microgravity condition (a reduction of the peak vertical force by about a factor 9) almost instantaneously.

Additionally, there was no significant interaction between the first compared with last three trials factor and the box size, for vertical box acceleration ($F_{1,32}$=0.05, P=0.833), for vertical box speed ($F_{1,32}$=0.06, P=0.810), or for the vertical force ($F_{1,26}$=0.15, P=0.704). Comparably low F-values were found for the two-way and three-way interactions between subject, box size, and first compared with last three trials. This provides a further indication that the elevated initial lifting effort in the larger box is preserved under microgravity.

Subject effects in the initial lifting period

Significant subjects effects were found for all investigated parameters in the initial lifting period (Table 1). Additionally, the pooled g_0 and g_1 data showed a significant box size with subject interaction for the vertical box acceleration and a significant three-way interaction between gravity condition, box size, and subject (Table 1). The separate ANOVAs on the gravity conditions showed that the subject with box-size interaction could mainly be attributed to the normal gravity condition. For the normal gravity condition, the box size with subject interaction was significant for the vertical box force ($F_{3,29}$=3.9, P=0.018) and

Table 1 Overall ANOVAs on averaged values of the first 200 ms after the first visible upward box movement for the vertical box acceleration, vertical box speed, and the vertical box force. F-values, P-values and df are given for the effects of gravity condition, box size, subject, and the interactions

Effect (df)	Box accn		Box speed		Box $F_{vert.}$	
	$F(df,78)$	P	$F(df,78)$	P	$F(df,78)$	P
Condition (1)	87.8	<0.001	28.3	<0.001	5065.0	<0.001
Box-size (1)	13.3	<0.001	17.0	<0.001	4.6	0.036
Subject (3)	13.2	<0.001	10.3	<0.001	225.5	<0.001
Condition×box-size (3)	0.7	0.397	0.1	0.806	0.8	0.865
Condition×subject (3)	3.2	0.029	1.5	0.230	2.1	0.109
Box-size×subject (3)	4.9	0.004	2.1	0.106	2.2	0.094
Condition×box-size×subject (3)	0.9	0.464	1.8	0.151	1.7	0.183

Table 2 Separate ANOVAs on both gravity conditions for averaged values of the first 200 ms after the first visible upward box movement for the vertical box acceleration, vertical box speed and vertical box force. Box size and subject were used as factors

Box-size effect	g_0			g_1		
	df	F	P	df	F	P
Acceleration	1,46	5.0	0.030	1,32	7.9	0.008
Speed	1,46	13.2	<0.001	1,32	5.4	0.027
$F_{vertical}$	1,38	2.0	0.169	1,29	2.7	0.109

box acceleration ($F_{3,32}$=3.8, P=0.020). This was not the case for the microgravity condition ($F_{3,38}$=0.5, P=0.663 and $F_{3,46}$=1.2, P=0.336, respectively).

Reaction to the enlarged initial lifting effort in the larger box

Over both gravity conditions, the peak upward box speed, occurring about 1 s after lift-off, was 0.1 m/s higher for the large box than the small one ($F_{1,78}$=8.6, P=0.004). This indicates that the subjects did compensate only partially for the initial box speed overshoot. Shortly after this peak upward speed, a negative box acceleration peak occurred, to decelerate the box. This deceleration peak was 0.62 m/s^2 higher for the large box than the small one ($F_{1,78}$=16,1, P<0.001). Comparabley, the peak upward acceleration shortly after lift-off was 0.65 m/s^2 higher in the large box. Due to the variations in timing of the deceleration peak, the enlarged deceleration in the larger box is not clearly visible in the averaged signals (Fig. 2). As in the initial parameters, no significant interactions between gravity condition and box size were found for the peak box speed and positive and negative acceleration. The resulting total vertical box displacement was not significantly different between the boxes ($F_{1,78}$=1.1, P=0.307).

In ANOVAs on the separate gravity conditions, the higher positive and negative acceleration peaks in the large box compared with the small one were confirmed for normal gravity ($F_{1,32}$=9.7, P=0.005) as well as microgravity ($F_{1,46}$=4.2, P=0.047). The peak upward box velocity was higher for the large box under microgravity ($F_{1,46}$=5.5, P=0.024) and showed a nonsignificant tendency to be higher for the large box under normal gravity ($F_{1,32}$=3.4, P=0.076).

Discussion

The reduction of the overall box movement speed found under microgravity is not surprising, since subjects will have to rely much more on feedback in order to produce adequate muscle forces. In addition, once an object is moving upward with a certain speed, it may be difficult to stop it under microgravity, whereas gravity is used to decelerate movement under normal conditions.

Despite the overall reduction of movement speed, the box speed and box acceleration during the first 200 ms after lift-off show convincingly that the effect of object size on motor preparation for lifting is preserved under microgravity conditions. Figure 2 shows comparable effects in the force signal. However, the trend of higher vertical forces in the large box was not significant when the gravity conditions were tested separately, although the pooled gravity conditions showed an overall effect of box size and no interaction between box size and gravity condition. The lack of significance of the box size in the tests per gravity condition may have been due to a variety of reasons. First, under microgravity a less favorable signal-to-noise ratio and the loss of force signals in 8 out of 54 trials may have resulted in a reduced statistical power. Second, under normal gravity, the rate of change of the vertical force is very high during the start of the box movement, due to the fact that the weight has to be counteracted before any movement takes place. Then, small deviations in the determination of the instant at which the box starts to move result in high variability in the mean vertical force during the first 100 ms. To illustrate this, the mean force during the first and second 100 ms after the start of the box movement were tested separately for the normal gravity condition. No effects of box size were found during the first 100 ms ($F_{1,29}$=0.2, P=0.662). In contrast, the second 100 ms showed a significant effect of box size on the vertical force ($F_{1,29}$=10.0, P=0.004). In all, it seems reasonable to conclude that there was a trend toward an effect of box size on the vertical force in both gravity conditions.

Compared with previous studies, the current study used relatively heavy objects. With lighter objects, the elevated initial effort in the larger box might be more pronounced since the size-weight illusion is known to increase with a reduction of object mass (Jones 1986; Stevens and Rubin 1970).

Since the vertical box acceleration showed an interaction effect between subject and box size (Table 1), the magnitude of the effect of object size on motor preparation in lifting can differ between subjects. However, subjects with box-size interactions were only visible in the normal gravity condition. In addition, no learning effects (the first compared with the last three trials) or learning with subject interactions were found under microgravity. Thus, the effect of object size on the initial lifting effort seemed stable within as well as between subjects under microgravity.

Savelsbergh et al. (1996) showed that a more careful approaching movement, which is used to pick up apparently fragile objects, completely disappears within 7 trials when the subjects experience that the object is in fact not fragile. Johansson and Westling (1988) showed that in lifting tasks with unexpected weight changes the applied force in a lifting movement primarily relies on the weight in the previous lift. In novel objects of unknown weight, lift and grip forces stabilize at a new level within two or three trials (Gordon et al. 1993). In addition, Toussaint et al. (1998) found anticipatory postural adjustments in whole-body lifting movements to be adapted to new loads within four trials. Thus, the programming of parameters concerning the expected forces is updated quite fast. Most likely, if the effect of object size on the initial box acceleration was only due to an inadequate adaptation to microgravity conditions, it would extinguish in a few lifting movements under microgravity. However, the current study showed no reduction of the size effect in the last three trials compared with the first three trials under microgravity, whereas the adaptation of the lifting force to the disappearance of gravity seemed almost instantaneous.

In conclusion, the results of the current study show that the elevated initial lifting effort in larger boxes holds during brief periods of microgravity. Moreover, (micro)gravity does not seem to influence the relative strength of the size effect on the initial box acceleration. This is indicated by the lack of interaction effects between box size and gravity condition on any of the investigated parameters. This suggests that, under normal gravity, the persistence of the elevated initial lifting effort under knowledge of equal box mass is related to a persistent upward scaling of the force component necessary to accelerate the object rather than the force component necessary to hold the object. However, more evidence is necessary before conclusions can be drawn at this point, since there are other possible explanations for the findings in the current study. For instance, the subjects may not have been able to completely eliminate the force component related to the object weight under microgravity but simply have reduced the initial lifting force with a constant value compared with normal gravity, irrespective of the object to be lifted. In that case, attributing the persisent elevated initial lifting effort under normal gravity largely to the force component related to acceleration of the object would not be justified. Given the usually concurrent appearance of the elevated initial lifting effort and the size-weight illusion in a larger box, it can be speculated that the size-weight illusion will also hold under microgravity. It could also be speculated that the elevated initial forces in the manipulation of larger objects will still hold in prolonged exposure to microgravity, implying that the volume of objects matters on Earth as well as for astronauts. In the absence of gravity, it may often be difficult to produce "external" forces that can break a movement once it started. Consequently, any excess force application in the manipulation of objects may result in undesirable floating of objects and/or the astronaut. The current study shows that under microgravity as well as normal gravity the application of such excess forces is more likely to occur in the manipulation of large objects than in the manipulation of small objects. Thus, particularly with manipulation of voluminous objects, it might be important for astronauts to slow down their movements.

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Appendix

For simplicity it is assumed that g=10 m/s^2. In addition, it is assumed that a small box of 10 kg is given an initial acceleration of 2 m/s^2. According to Eq. 1, the lifting force, applied to the object just after lift-off, can than be calculated as:

$$f = m \times g + m \times a = 10 \times 10 + 10 \times 2 = 120\,\text{N}.$$

In addition, let us assume that an initial acceleration of the large box of 3.2 m/s^2 is found. The initial lifting force would then be:

$$10 \times 10 + 10 \times 3.2 = 132\,\text{N}.$$

However, if the subject was asked to lift the large box at the same speed as the small one, the subject may have tried to accelerate the box with 2 m/s^2. The initial lifting force of 132 N in the large box could then be caused by:

1. An 11.2% upward scaling of only the object weight: $11.2 \times 10 + 10 \times 2 = 132$ N
2. A 60% upward scaling of only the object inertial mass: $10 \times 10 + 16 \times 2 = 132$ N
3. A 10% upward scaling of both the object weight and the inertial mass: $11 \times 10 + 11 \times 2 = 132$ N.

Under microgravity, the weight of the object disappears. If the subject is able to adapt to this circumstance by eliminating the weight-related force component, cases 1, 2, and 3 would result in different object accelerations, since the actual inertial mass of the large object was 10 kg. The elevated initial acceleration in the large object would: completely disappear in case 1, since a=(10×2)/10=2 m/s^2; persist in case 2, since a=(16×2)/10=3.2 m/s^2; and strongly be reduced in case 3, since a=(11×2)/10=2.2 m/s^2.

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